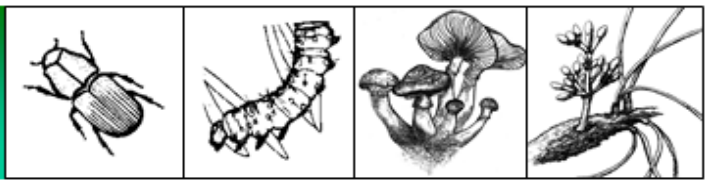
Forest Health Protection



21-02 *MAY, 2021*

Predicting stand-level lodgepole pine mortality from mountain pine beetle outbreak from plots monitored 2006-2012 across Helena National Forest

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Executive Summary

Resource managers need tools to predict lodgepole (*Pinus contorta*) and ponderosa (*Pinus ponderosa*) pine mortality caused by mountain pine beetle (*Dendroctonus ponderosae* Hopkins) (MPB) at stand-level scales during outbreaks (i.e. high beetle population pressure) and drought. The 1999-2015 extensive MPB outbreak on the Helena National Forest (HNF) coincided with protracted drought and establishment of intensified forest inventory and analysis (FIA) plots that were monitored along with the temporal progression of the MPB outbreak. Collected data were assessed to identify influential forest conditions and climate variables related to the pine mortality event.

A predictive loss model with corresponding prediction intervals was developed for lodgepole pine stands exposed to outbreak levels of MPB. Best-fit model parameters included lodgepole pine basal area (BA), quadratic mean diameter (QMD), and a soil aridity index. We were unable to develop a statistically rigorous predictive model for loss of ponderosa pine, although high ponderosa pine BA and QMD were associated with greater proportional losses of ponderosa pine. Thirteen and 26% of plots with lodgepole and ponderosa pine, respectively, experienced no pine mortality, which indicates that even with severe beetle pressure, MPB did not eliminate all suitable hosts in the HNF during this outbreak. Mature pine that remains, especially moderate and high hazard stands with high densities of larger diameter pines may be vulnerable to MPB during the next drought.

Introduction

Many forests in western North America have simultaneously become vulnerable to disturbance in recent decades. MPB is the most prominent and damaging biotic disturbance agent in western North America. MPB fulfills its ecological role by killing decadent, aging, or otherwise stressed pine, in scattered, small groups of trees when beetle populations are at non-outbreak, endemic levels. At epidemic levels,

United States Department of Agriculture	Forest Service	Northern Region	Region One 26 Fort Missoula Rd Missoula, MT 59804-7203	

landscape-scale outbreaks that kill large portions of overstory pine occur every 15-25 years in the USFS Northern Region (Harley et al. 2019; Jenne and Egan 2019; Lestina et al. 2020). MPB outbreaks usually correspond with drought, although stand maturity and overstocking render forests more susceptible to MPB. The recent MPB outbreak, 1999-2015, was the most damaging on record in the Northern Region (Lestina et al. 2020) and elsewhere in western North America (Bentz et al. 2009). There is a need to better quantify and predict pine losses to MPB during outbreaks at a stand-level across varying structure, composition, topography, and climate conditions. This will help to specify management activities at the local scale and prioritize areas most vulnerable to MPB.

A general understanding of forest composition and structure that is of high hazard (i.e. highly vulnerable) to MPB, should there be an outbreak, allows forest managers to identify MPB-susceptible forests at various scales. These hazard ratings are available forest wide for the Northern Region (USFS Region 1) at the mid-level (Steed et al. 2019), as well as for assessment at the stand-level (Randall et al. 2019). Hazard ratings do not consider MPB population pressure or ambient weather/climate conditions (i.e. risk) and their contribution to pine mortality. Evaluation of how well hazard ratings predicted mortality following a MPB outbreak can guide adjustments to improve their utility.

Available models that predict pine losses to MPB include parameters for stand conditions, such as BA and stem density (Cole and McGregor 1983; Shore et al. 2000; Negrón and Popp 2004). They do not, however, include parameters for climate or drought conditions, a knowledge of which will be especially important in light of rapidly changing climate conditions and future projections of increased temperatures and incidence of drought in western North America (Fettig et al. 2013; USGCRP 2018). Fine-scale forest conditions data and inclusion of moisture indices as parameters in pine loss models to MPB, measured when MPB populations are high, will improve predictions for future MPB impacts.

Our main objective was to identify levels of mortality that can be expected by land managers for similar forest attributes as those in the HNF during similar conditions, i.e. drought and high MPB population pressure. We used intensified FIA grid data in the HNF that collected spatially balanced and temporally detailed data on stand structure, composition, and tree mortality within lodgepole and ponderosa pine forests during an extensive MPB outbreak (primarily 2006-2012) that coincided with drought. Our specific objectives were to:

1. Quantify impacts of the 2006-2012 MPB outbreak in the study area.
2. Relate stand and landscape-scale MPB hazard ratings assigned prior to the outbreak to actual mortality levels.
3. Identify stand, tree, and soil moisture aridity neighborhood factors associated with MPB-caused mortality and develop predictive models to estimate lodgepole and ponderosa pine losses (mortality) during future MPB outbreaks.

Methods

In 2006 and 2007, the HNF funded FIA contract crews to establish a 4x intensified grid with a total of 305 1/24th ac (24.7-ft radius) fixed plots (see Bechtold and Patterson 2005) distributed across the Divide and Elkhorn Mountains as well as 88 plots within a 48x intensified grid in the Warm Springs creek drainage. Plots were distributed in a spatially balanced manner that averaged one plot every 1,700 ac within the 4x grid and one plot every 102 ac within the 48x grid (Fig. 1, Table 1). Candidate variables for selection in explanatory and predictive models that influenced mortality at the tree, plot, site, and watershed scales are listed in Table 2.

Table 1. 1/24th acre (24.7 ft radius) fixed-area plots by forested composition that were established 2006-2008 and re-measured post-MPB outbreak in 2012.

Plot Location	Forested plots	Plots with pine	Plots with lodgepole pine	Plots with ponderosa pine
Elkhorn (4x)	44	35	29	5
Divide (4x)	76	65	63	2
Warm Springs (48x) within Elkhorns	82	67	18	52
Totals	202	167	110	59

Establishment of the intensified grid coincided with the start of the MPB epidemic and corresponding drought (Fig. 2). MPB populations caused extensive mortality in pure and mixed stands of lodgepole and ponderosa pine within the study area (Fig. 1). The HNF prioritized areas for intensified grid plot establishment from 2006 to 2008 that virtually followed the progression of MPB-caused mortality (Fig. 1). A partial re-measurement of these plots occurred from 2008 to 2010 and full re-measurement in 2012 (Table 1).

Table 2. Candidate explanatory and predictive variables used in models.

Spatial	Variable
Tree	Diameter at Breast Height, DBH (in)
	Species
	Height (ft)
	Age (y)
	MPB status
	Snag status
Plot	Regeneration species composition
	Regeneration density (stems per ac)
	Stem density (trees per ac)
	Tree density (stems per ac; BA per ac; stand density index, SDI)
	Species composition
	Stem diameter (mean DBH; quadradic mean diameter, QMD)
	Tree height (mean in ft by diameter class)
	Age (mean in y by diameter class)
	MPB hazard rating (Randall et al. 2019)
	MPB-caused mortality (stems per ac; BA per ac)
Site	Clear sky incident solar radiation (aspect/slope derivative)
	Topographic position
	Elevation (ft)
	Geospatial coordinates (latitude, longitude)
	30-y mean climatic water balance deficit
	30-y mean evapotranspiration
	30-y mean minimum temperature (°F, Anusplin)
	30-y mean precipitation (in, Anusplin)
	Soil Aridity Indices across various Neighborhood sizes
Watershed	Aspect (overall/majority)
	Surrounding forest composition
	Water stress assessment

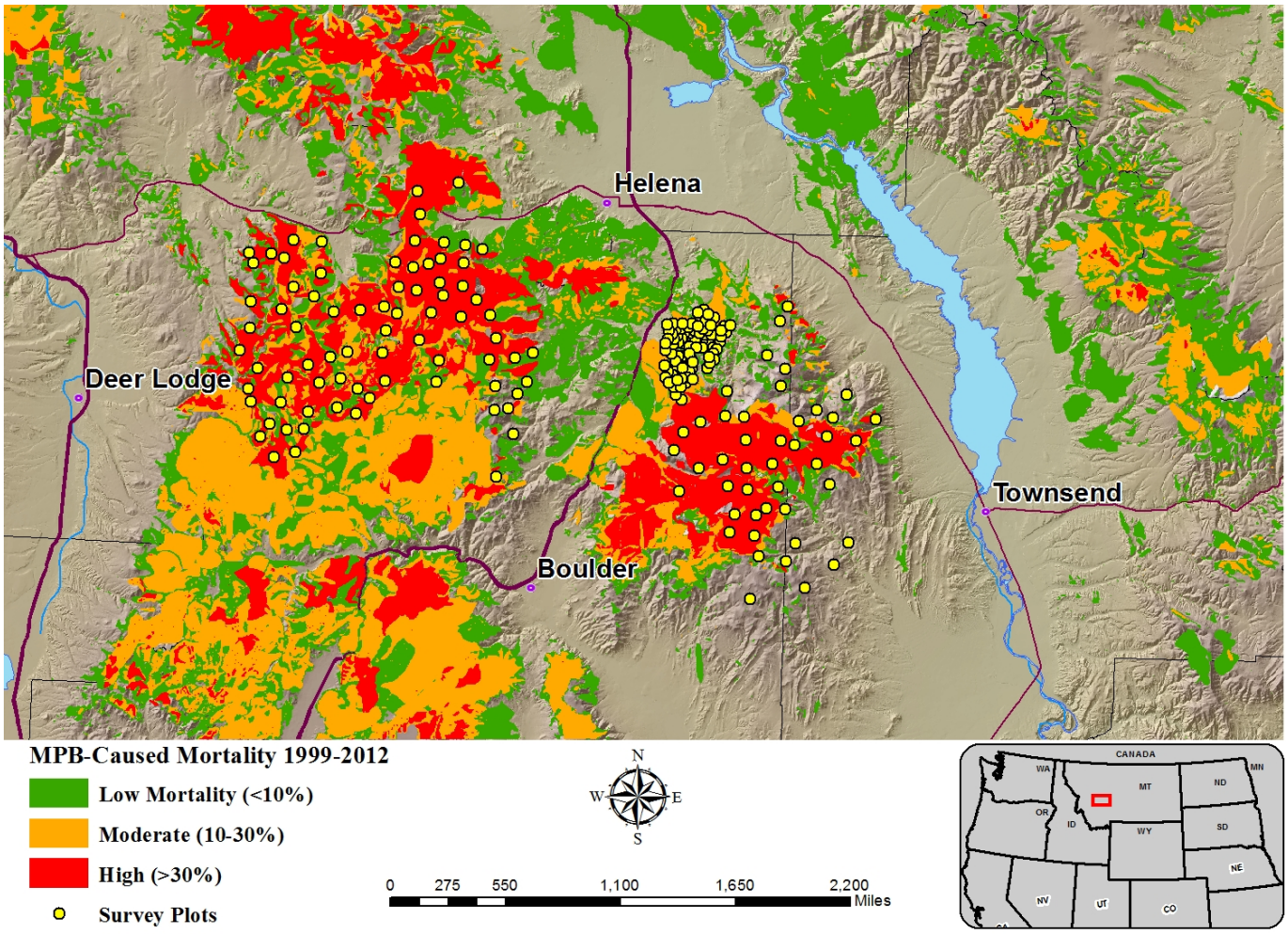

Figure 1. Map showing distribution of plots established 2006-2008 and Aerial Detection Survey estimated MPB-impact 1999-2012, western Helena National Forest.

Mortality and plot attribute data were used to reconstruct stand conditions in years immediately preceding the MPB outbreak. For this, mortality data collected during plot establishment (2006-2008) was combined with live-tree data to calculate stand attributes (stand density, QMD, etc.) representing early 2000s conditions. Mortality data were used to calculate response variables (trees per acre and BA killed by MPBs) for modeling and for spatial interpolation assessment. Soil aridity index values were calculated from downscaled, geoclimatic data at various neighborhood sizes surrounding plots (i.e., diss7 refers to 7x 30x30m^2 grid cells immediately surrounding each plot).

Exploratory analysis used Pearson correlations among similar tree, plot, site, and watershed scale variables to determine which variables were correlated and could be substituted for one another in models (e.g. TPA vs. BA). If similar variables were highly correlated, the variable more often collected in forest stand exams was used in candidate models to avoid collinearity issues. Tests for spatial autocorrelation of mortality at the plot level were also conducted to determine whether spatial statistical parameters were needed to reduce spatial co-variance.

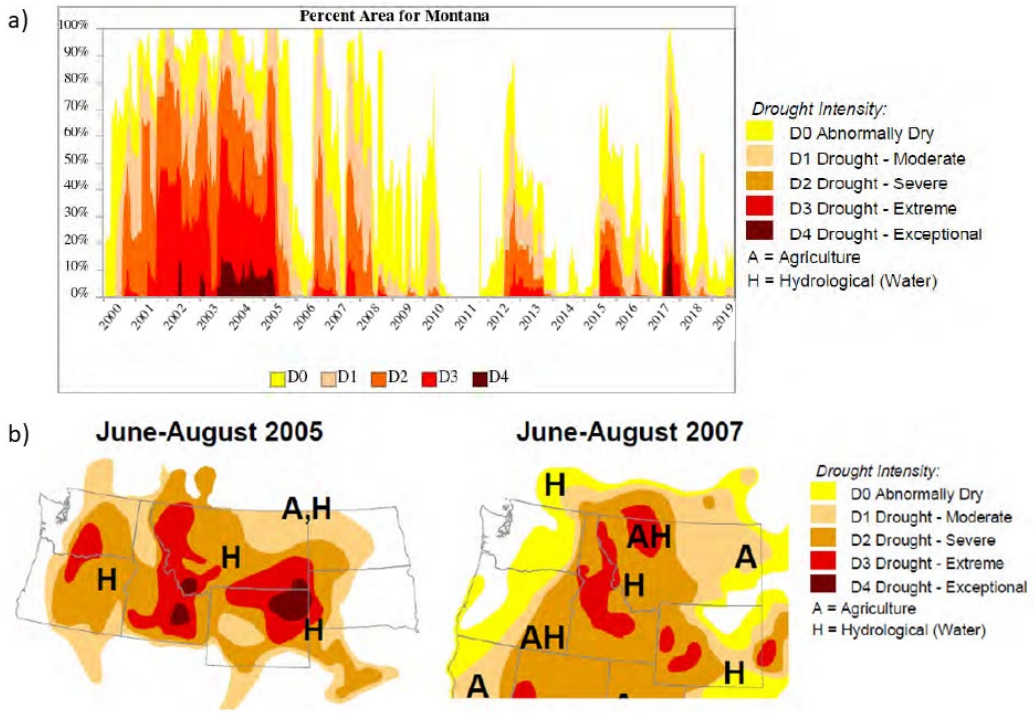

Figure 2. Palmer drought severity indices for (a) the state of Montana 2000 – 2019, and (b) spatial pattern of drought severity in the northwestern U.S. during summers of 2005 and 2007. Colors represent intensity of drought according to the legend (right). Source: drought.gov

Join-count test of spatial autocorrelation using several different types of spatial neighborhoods based on the distance of separation between the plots, and Moran's I and Geary's C statistics indicated no evidence of spatial autocorrelation of pine mortality among plots. Classification trees, random forests, and logistic regression models were considered to derive best-fit models, evaluating mortality as both a binary and continuous response. Nonlinear logistic regression with mortality as a continuous response provided the most explanatory and predictive power. The final model for lodgepole pine was chosen using a hybrid stepwise AIC approach with 10-fold cross-validation. Models developed for ponderosa pine mortality had limited predictive power and were not explored further for use.

Results and Discussion

Mountain Pine Beetle Outbreak Impacts

Between 2001 and 2012, there was a bimodal distribution of cumulative pine mortality. Many plots had either low or high levels of mortality, with few plots between these extremes (Fig. 3). Thirteen (13%) plots that contained lodgepole pine experienced no mortality from MPB, and 37 (37%) experienced ≥90% mortality of lodgepole pine BA. In plots with lodgepole pine, trees in all diameter classes were killed, though proportionately more from the larger diameter classes (Fig. 4). Spatially, there was substantial mortality in lodgepole pine in South Divide, some pockets of mortality in the Elkhorns, and very little mortality in Warm Springs (Fig. 5a). Ponderosa pine was more common in Warm Springs and comprised much of the pine mortality there (Fig. 5a vs. b).

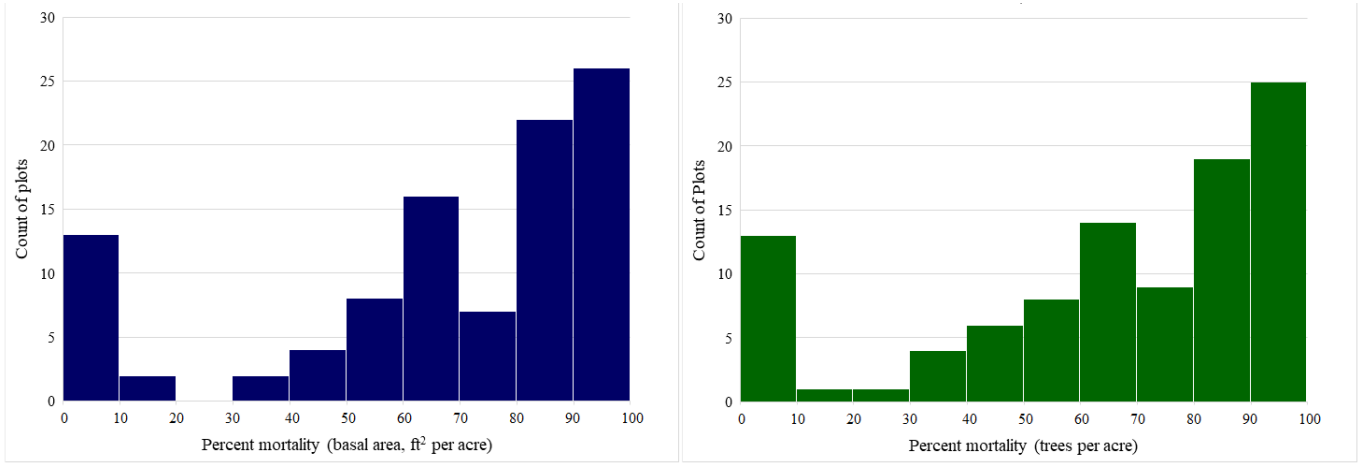

Figure 3. Frequency distributions of the number of plots with lodgepole pine by amount of MPB-caused mortality measured in (left) basal area and (right) stem density (trees per acre).

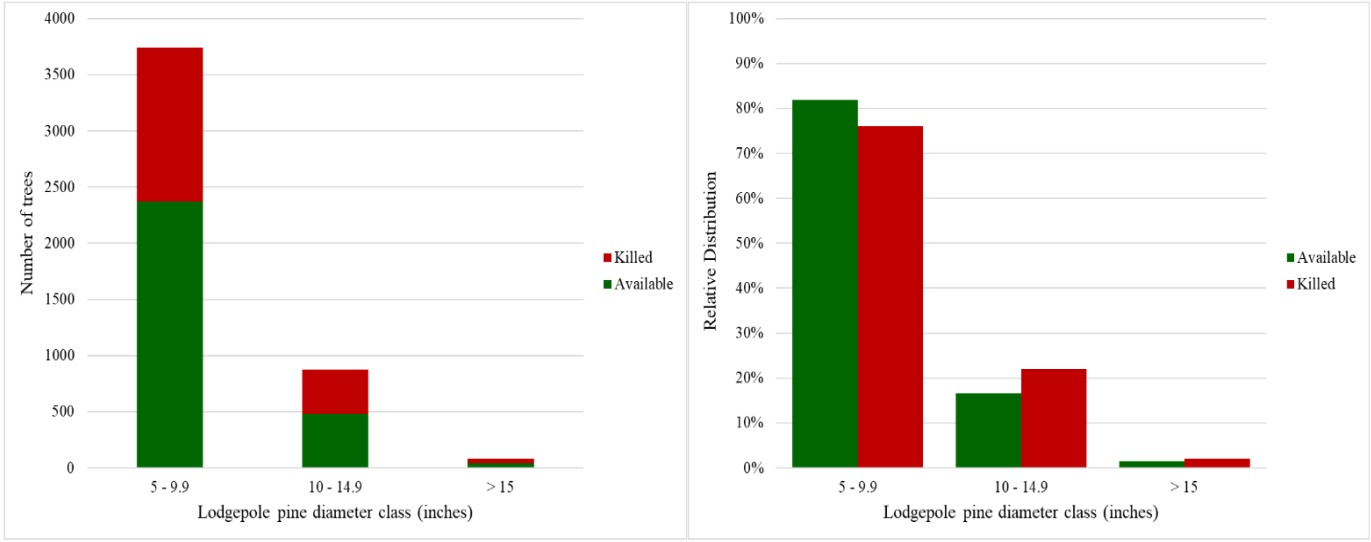

Figure 4. Among all plots with lodgepole pine, distribution of (left) the number of trees and (right) relative percentage by diameter class that were available (alive, reconstructed to pre-outbreak early 2000s) vs. killed by MPB by 2012.

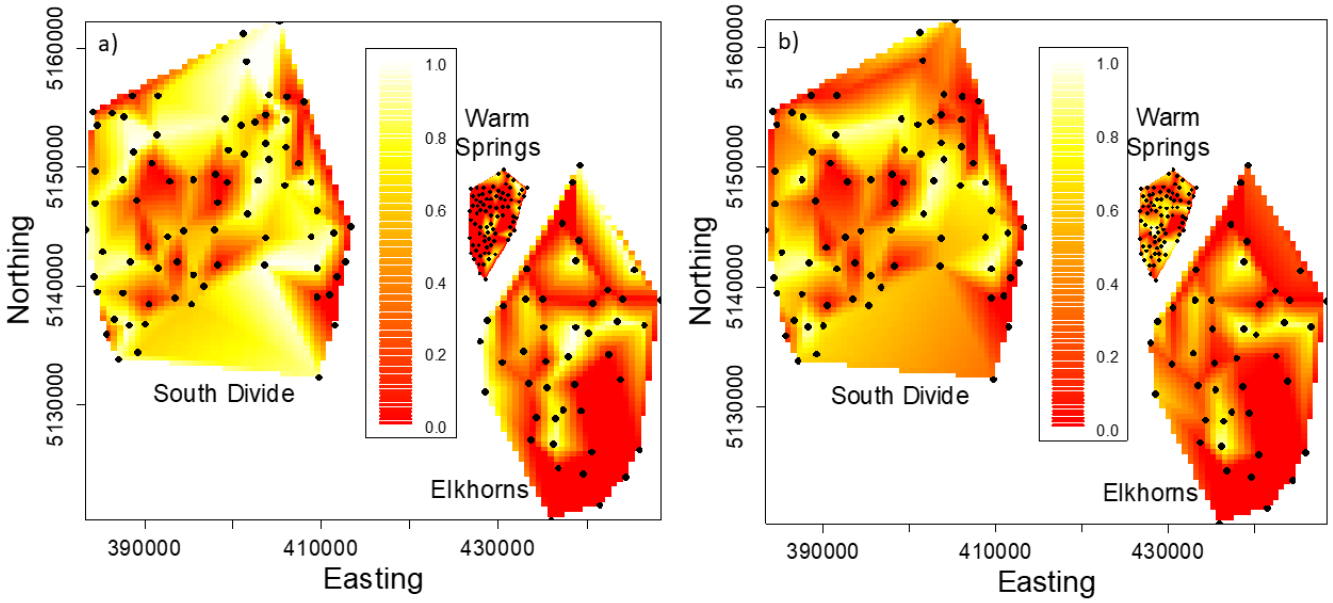

Figure 5. Density plot showing spatially interpolated hotspots of MPB-caused mortality for (a) lodgepole pine in South Divide and Warm Springs areas and (b) all pines in Warm Springs area, cumulative from 2006 to 2012 in the western Helena National Forest.

For both lodgepole and ponderosa pine, mortality tended to be greater in plots with higher hazard ratings in 2001, although there were some plots rated moderate or high hazard that experienced either 0 or 100% mortality (Fig. 6). Of the three components of hazard ratings, QMD and BA were used in the candidate and final explanatory models for lodgepole pine; species composition was not influential enough for model inclusion. Interestingly, ponderosa pine median mortality rates were similar for moderate and high hazard plots (Fig. 6b), suggesting drought conditions enhanced vulnerability in both moderate and high hazard stands similarly during this outbreak.

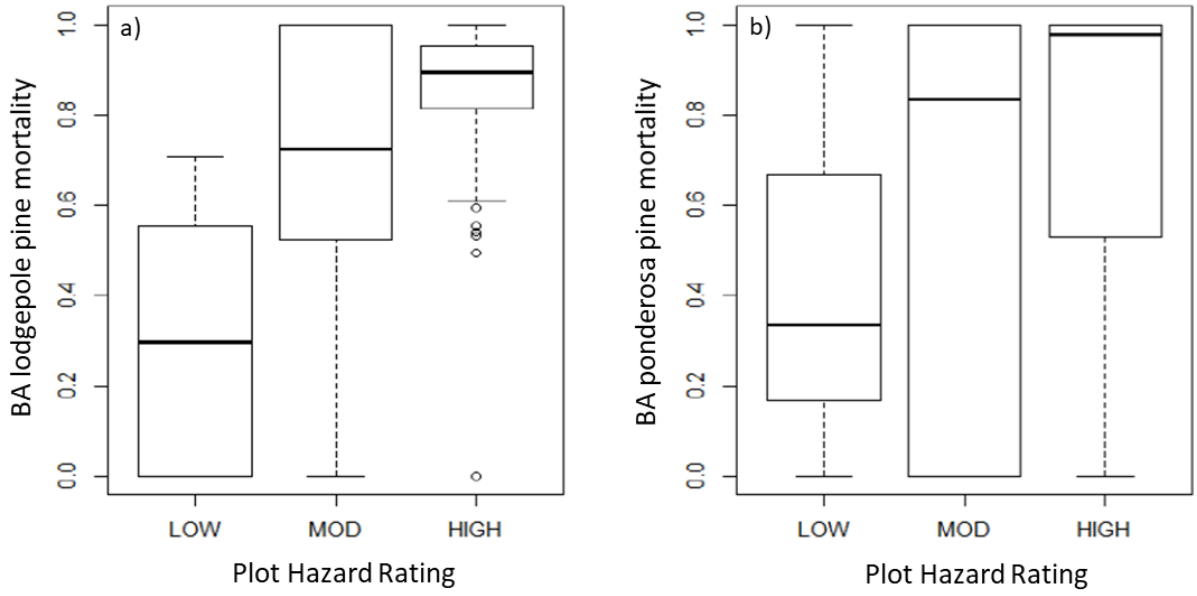

Figure 6. Boxplots of the proportion of pine basal area mortality (solid line = median; bounds of boxes = 1st and 3rd quartiles), by plot-level MPB hazard rating (Randall et al. 2019) in 2001 for (a) lodgepole and (b) ponderosa pine.

Predictive Model Building

Candidate models developed for ponderosa pine losses due to MPB had limited predictive power, and so were not developed further. However, it is worth noting that QMD and BA had the most explanatory power while none of the aridity indices were useful.

Models for lodgepole pine losses due to MPB had similar explanatory and predictive power when the parameter TPA or BA was used; BA was chosen over TPA as a more robust measure of tree-to-tree competition. A model with parameters lodgepole pine BA, QMD, and aridity index diss7 provided the best predictive power for the proportion of lodgepole pine BA mortality caused by MPB (Figs. 7-9):

$$P(\widehat{Mortality}) = \frac{\exp(-6.67 + 0.630(QMD) + 0.0094(BA) + 3.26(diss7)}{1 + \exp(-6.67 + 0.630(QMD) + 0.0094(BA) + 3.26(diss7)}$$

This model reduced the predicted error sum of squares (PRESS) by 41.4%, meaning that the error was only 58.6% of that for a model with no predictors (i.e. the null model). QMD was most influential on predicted lodgepole pine mortality (Fig. 7), although BA was also highly influential (Fig. 8). Soil aridity, as measured by dissection index (7x7 30m^2 cells in neighborhood), significantly influenced predicted lodgepole pine mortality as well, though far less dramatically than QMD or BA. Stands with large diameter trees and/or high BA, are predicted to lose the majority of lodgepole pine BA, even when indices indicated wetter conditions (Fig. 9). This soil aridity statistic is representative of relative topographic impressions and depressions and end-users can use assumed .37 value for stands located in depressions (i.e. valley-bottoms) and 0.67 for stands on impressions (i.e. sloped topography and ridge-tops).

A spreadsheet tool has been programmed for resource managers to predict losses from MPB outbreaks of similar magnitude during drought conditions. This tool can be requested by contacting Forest Health Protection staff in Missoula, MT or through this Box-link, accessible to internal U.S. Forest Service employees: Link to MPB Loss Prediction tool within U.S. Forest Service Box network

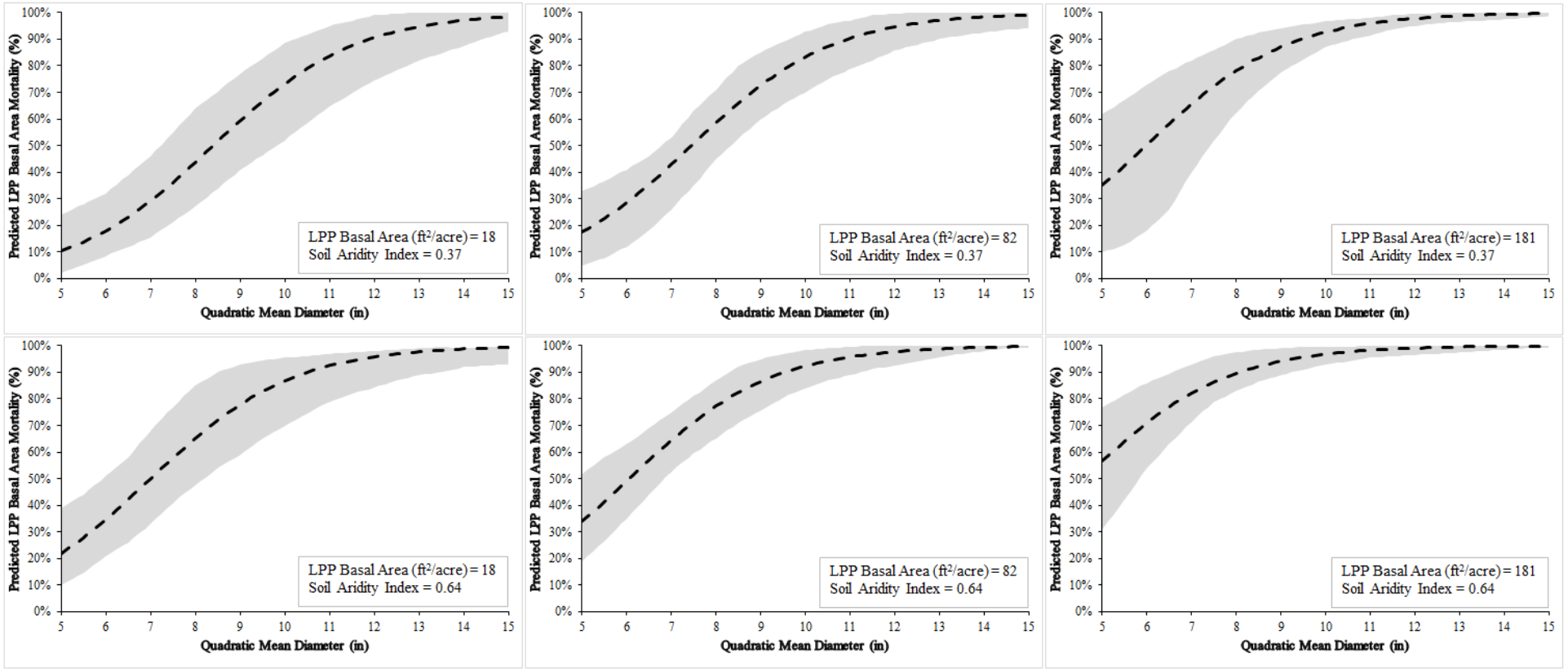
Predicted LPP Basal Area Mortality (%)
Quadratic Mean Diameter (in)
LPP Basal Area (ft²/acre) = 18
Soil Aridity Index = 0.37
LPP Basal Area (ft²/acre) = 82
Soil Aridity Index = 0.37
LPP Basal Area (ft²/acre) = 181
Soil Aridity Index = 0.37
LPP Basal Area (ft²/acre) = 18
Soil Aridity Index = 0.64
LPP Basal Area (ft²/acre) = 82
Soil Aridity Index = 0.64
LPP Basal Area (ft²/acre) = 181
Soil Aridity Index = 0.64

Figure 7. Predicted MPB-caused lodgepole pine mortality (dashed line) and 95% prediction intervals (gray shading) as a function of QMD, by the 10th, 50th, and 90th percentiles of BA (columns) and soil aridity index (rows).

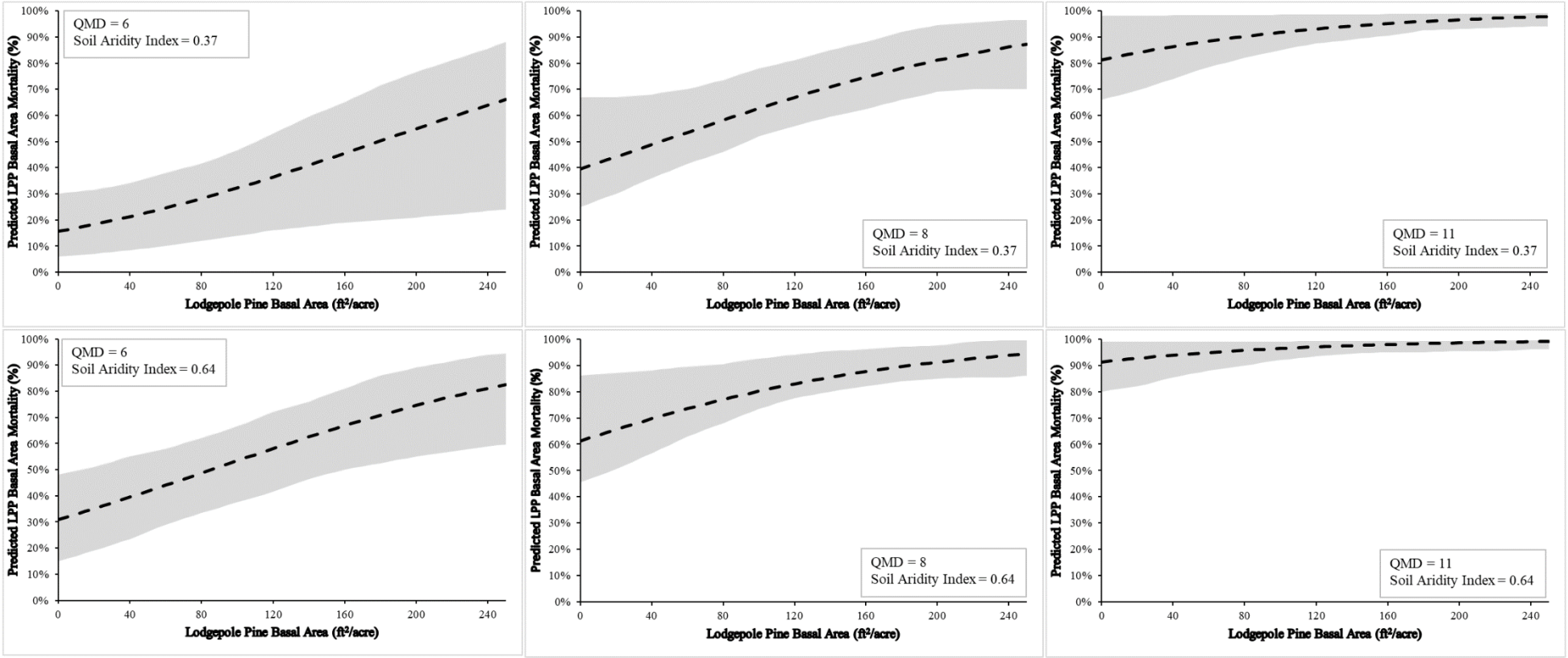

Figure 8. Predicted MPB-caused lodgepole pine mortality (dashed line) and 95% prediction intervals (gray shading) as a function of BA, by the 10th, 50th, and 90th percentiles of QMD (columns) and soil aridity index (rows).

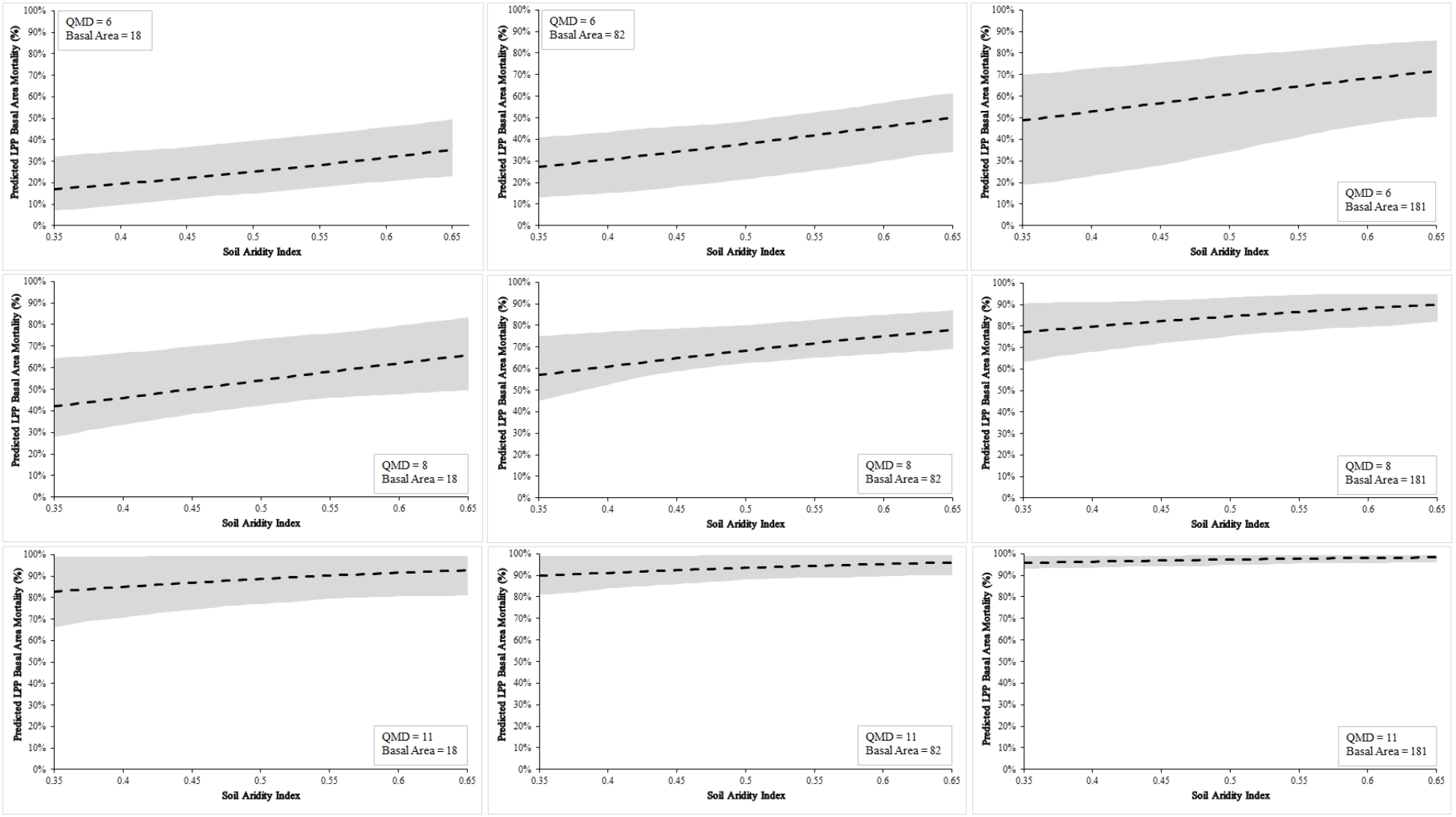
QMD = 6
Basal Area = 18
QMD = 6
Basal Area = 82
QMD = 6
Basal Area = 181
QMD = 8
Basal Area = 18
QMD = 8
Basal Area = 82
QMD = 8
Basal Area = 181
QMD = 11
Basal Area = 18
QMD = 11
Basal Area = 82
QMD = 11
Basal Area = 181
Predicted LPP Basal Area Mortality (%)
Soil Aridity Index
0% 10% 20% 30% 40% 50% 60% 70% 80% 90% 100%
0.35 0.4 0.45 0.5 0.55 0.6 0.65

Figure 9. Predicted MPB-caused lodgepole pine mortality (dashed line) and 95% prediction intervals (gray shading) as a function of soil aridity index, by the 10th, 50th, and 90th percentiles of QMD (columns) and BA (rows).

Conclusions

Approximately one-third and one-half of intensified FIA plots on the HNF that contained lodgepole and ponderosa pine, respectively, experienced >90% mortality between 2001 and 2012. However, mortality was variable as 13% and 26% of plots with lodgepole and ponderosa pine, respectively, experienced no pine mortality during the outbreak, even with high beetle population pressure and trees physiologically stressed by drought. This indicates a small portion of the landscape was 'missed' by bark beetles by random chance, or due to unknown biological or physical reasons. Regardless, this finding is critical information to inform MPB occurrence assumptions for broad- to national-level risk assessments, such as the National Insect and Disease Forest Risk Assessment (Krist et al. 2014). As MPBs did not eliminate all suitable hosts on the landscape, resource managers can expect some pine forests, especially those with moderate to high hazard ratings, will be vulnerable to MPB during the next drought.

A predictive model and corresponding prediction intervals were developed for lodgepole pine losses during high MPB population pressure. We were unable to develop a similar predictive model for loss of ponderosa pine, although high ponderosa pine BA and QMD were associated with greater proportional losses of ponderosa pine. Few plots (59 ponderosa pine plots vs. 110 for lodgepole pine; Table 1), small plot size ($1/24^{th}$ ac), and bimodal mortality distribution (across which moderate hazard plots either had high or minimal mortality rates) were factors that prevented modelling of ponderosa pine loss.

Lodgepole pine model parameters included lodgepole pine BA, QMD (both are included in current Northern Region MPB hazard ratings), and a soil aridity index, diss7. This model is similar to other lodgepole pine loss models in that stands with high densities of larger diameter trees are most likely to experience substantial losses from MPB (Cole and McGregor 1983; Shore et al. 2000; Negrón and Popp 2004). This model's added benefit is its calibration with spatially balanced plots established across a multi-million acre extent during a modern period of severe drought. Utility of this model ranges from stand-level predictions for silvicultural manager-use to strategic planning efforts to predict lodgepole pine mortality across landscape-plot distributions, when forest conditions are similar to those surveyed in the western HNF during drought and when MPB risk is high.

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